

$B \rightarrow K\pi$  DECAYS AND THE WEAK PHASE ANGLE  $\gamma^\dagger$ **T. N. Pham**

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## ABSTRACT

The large branching ratios for  $B \rightarrow K\pi$  decays as observed by the CLEO Collaboration indicate that penguin interactions contribute a major part to the decay rates and provide an interference between the Cabibbo-suppressed tree and penguin contributions resulting in a CP-asymmetry between the  $B \rightarrow K\pi$  and its charge conjugate mode. The CP-averaged decay rates depend also on the weak phase  $\gamma$  and give us a determination of this phase. In this talk, I would like to report on a recent analysis of  $B \rightarrow K\pi$  decays using factorisation model with final state interaction phase shift included. We find that factorisation seems to describe qualitatively the latest CLEO data. We also obtain a relation for the branching ratios independent of the strength of the strong penguin interactions. This relation gives a central value of  $0.60 \times 10^{-5}$  for  $\mathcal{B}(\bar{B}^0 \rightarrow \bar{K}^0 \pi^0)$ , somewhat smaller than the latest CLEO measurement. We also find that a ratio obtained from the CP-averaged  $B \rightarrow K\pi$  decay rates could be used to test the factorisation model and to determine the weak angle  $\gamma$  with more precise data, though the latest CLEO data seem to favor  $\gamma$  in the range  $90^\circ - 120^\circ$ .

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With the measurement of all the four  $B \rightarrow K\pi$  branching ratios, we seem to have a qualitative understanding of the  $B \rightarrow K\pi$  decays. The measured CP-averaged branching ratios( $\mathcal{B}$ ) by the CLEO Collaboration [1] show that the penguin interactions dominates the  $B \rightarrow K\pi$  decays, as predicted by factorisation. The strong penguin amplitude, because of the large CKM factors, becomes much larger than the tree-level terms which are Cabibbo-suppressed and the non-leptonic interaction for  $B \rightarrow K\pi$  is dominated by an  $I = 1/2$  amplitude. This is borne out by the CLEO data which give  $\mathcal{B}(B^- \rightarrow \bar{K}^0 \pi^-) \simeq 2\mathcal{B}(B^- \rightarrow K^- \pi^0)$  and  $\mathcal{B}(B^- \rightarrow \bar{K}^0 \pi^-) \simeq \mathcal{B}(\bar{B}^0 \rightarrow K^- \pi^+)$  :

$$\begin{aligned}\mathcal{B}(B^+ \rightarrow K^+ \pi^0) &= (11.6_{-2.7-1.3}^{+3.0+1.4}) \times 10^{-6}, \\ \mathcal{B}(B^+ \rightarrow K^0 \pi^+) &= (18.2_{-4.0}^{+4.6} \pm 1.6) \times 10^{-6}, \\ \mathcal{B}(B^0 \rightarrow K^+ \pi^-) &= (17.2_{-2.4}^{+2.5} \pm 1.2) \times 10^{-6}, \\ \mathcal{B}(B^0 \rightarrow K^0 \pi^0) &= (14.6_{-5.1-3.3}^{+5.9+2.4}) \times 10^{-6}.\end{aligned}\tag{1}$$

If the strength of the interference between the tree-level and penguin contributions is known, a determination of the weak phase  $\gamma$  could be done in principle. Previous works [2, 3] shows that factorisation model produces sufficient  $B \rightarrow K\pi$  decay rates, in qualitative agreement with the CLEO measured values. Also, as argued in [4], for these very energetic decays, because of color transparency, factorisation should be a good approximation for  $B \rightarrow K\pi$  decays if the Wilson coefficients are evaluated at a scale  $\mu = O(m_b)$ . Infact, recent hard scattering calculations with perturbative QCD shows that factorisation is valid up to corrections of the order  $\Lambda_{\text{QCD}}/m_b$  [5]. It is thus encouraging to use factorisation to analyse the  $B \rightarrow K\pi$  decays, bearing in mind that there are important theoretical uncertainties in the long-distance hadronic matrix elements, as the heavy to light form factors for the vector current and the value of the current  $s$  quark mass are currently not determined with good accuracy. In this talk, I would like to report on a recent work [6] on the  $B \rightarrow K\pi$  decays as a possible way to measure the angle  $\gamma$  and to see direct CP violation.

In the standard model, the effective Hamiltonian for  $B \rightarrow K\pi$  decays are given by [7, 8, 9, 10, 11],

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} [V_{ub}V_{us}^*(c_1 O_1^u + c_2 O_2^u) + V_{cb}V_{cs}^*(c_1 O_1^c + c_2 O_2^c) - \sum_{i=3}^{10} V_{tb}V_{ts}^* c_i O_i] + \text{h.c.}.\tag{2}$$

in standard notation. At next-to-leading logarithms,  $c_i$  take the form of an effective Wilson coefficients  $c_i^{\text{eff}}$  which contain also the penguin contribution from the  $c$  quark loop and are given in [9, 11].

The parameters  $V_{ub}$  etc. are the flavor- changing charged current couplings of the weak gauge boson  $W^\pm$  with the quarks as given by the Cabibbo-Kobayashi-Maskawa

(CKM) quark mixing matrix  $V$ .  $V$  is usually defined as the unitary transformation relating the the weak interaction eigenstate of quarks to their mass eigenstate [12]:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad (3)$$

where  $d, s, b$  and  $d', s', b'$  are respectively the mass eigenstates and weak interaction eigenstates for the charge  $Q = -1/3$  quarks. Since the neutral current is not affected by the unitary transformation on the quark fields, flavor-changing neutral current is absent at the tree-level as implied by the GIM mechanism. The unitarity condition  $VV^\dagger = 1$  gives, for the (db) elements relevant to  $B$  decays [12]

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad (4)$$

This can be represented by a triangle [12] with the three angles  $\alpha, \beta$  and  $\gamma$  expressed in terms of the CKM matrix elements as [13]:

$$\begin{aligned} \alpha &= \arg(-V_{td}V_{tb}^*/V_{ud}V_{ub}^*) \\ \beta &= \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*) \\ \gamma &= \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*) \end{aligned} \quad (5)$$

The angle  $\gamma$  enters the  $B \rightarrow K\pi$  decay amplitudes through the factor  $V_{ub}V_{us}^*/V_{tb}V_{ts}^*$  which can be approximated by  $-(|V_{ub}|/|V_{cb}|) \times (|V_{cd}|/|V_{ud}|) \exp(-i\gamma)$  after neglecting terms of the order  $O(\lambda^5)$  in the (bs) unitarity triangle,  $\lambda$  being the Cabibbo angle in the Wolfenstein parametrisation of the CKM quark mixing matrix. The  $B \rightarrow K\pi$  decay amplitudes, expressed in terms of the  $I = 1/2$  and  $I = 3/2$  isospin amplitudes are given by [2],

$$\begin{aligned} A_{K^-\pi^0} &= \frac{2}{3}B_3e^{i\delta_3} + \sqrt{\frac{1}{3}}(A_1 + B_1)e^{i\delta_1}, \\ A_{\bar{K}^0\pi^-} &= \frac{\sqrt{2}}{3}B_3e^{i\delta_3} - \sqrt{\frac{2}{3}}(A_1 + B_1)e^{i\delta_1}, \\ A_{K^-\pi^+} &= \frac{\sqrt{2}}{3}B_3e^{i\delta_3} + \sqrt{\frac{2}{3}}(A_1 - B_1)e^{i\delta_1}, \\ A_{\bar{K}^0\pi^0} &= \frac{2}{3}B_3e^{i\delta_3} - \sqrt{\frac{1}{3}}(A_1 - B_1)e^{i\delta_1}, \end{aligned} \quad (6)$$

$A_1$  is the sum of the strong penguin  $A_1^S$  and the  $I = 0$  tree-level  $A_1^T$  as well as the  $I = 0$  electroweak penguin  $A_1^W$  contributions to the  $B \rightarrow K\pi$   $I = 1/2$  amplitude; similarly  $B_1$  is the sum of the  $I = 1$  tree-level  $B_1^T$  and electroweak penguin  $B_1^W$

contribution to the  $I = 1/2$  amplitude, and  $B_3$  is the sum of the  $I = 1$  tree-level  $B_3^T$  and electroweak penguin  $B_3^W$  contribution to the  $I = 3/2$  amplitude.  $\delta_1$  and  $\delta_3$  are, respectively, the elastic  $\pi K \rightarrow \pi K$   $I = 1/2$  and  $I = 3/2$  final state interaction (FSI) phase shift at the  $B$  mass. The inelastic FSI contributions are also included through the internal quark loop contributions to the penguin operators, for which the Wilson coefficients now have an absorptive part and are given in [9, 11, 14]. The  $B \rightarrow K\pi$  isospin amplitudes in the factorisation model are given by [2],

$$\begin{aligned}
A_1^T &= i \frac{\sqrt{3}}{4} V_{ub} V_{us}^* r a_2, \\
B_1^T &= i \frac{1}{2\sqrt{3}} V_{ub} V_{us}^* r \left[ -\frac{1}{2} a_2 + a_1 X \right], \\
B_3^T &= i \frac{1}{2} V_{ub} V_{us}^* r [a_2 + a_1 X], \\
A_1^S &= -i \frac{\sqrt{3}}{2} V_{tb} V_{ts}^* r [a_4 + a_6 Y], \quad B_1^S = B_3^S = 0, \\
A_1^W &= -i \frac{\sqrt{3}}{8} V_{tb} V_{ts}^* r [a_8 Y + a_{10}], \\
B_1^W &= i \frac{\sqrt{3}}{4} V_{tb} V_{ts}^* r \left[ \frac{1}{2} a_8 Y + \frac{1}{2} a_{10} + (a_7 - a_9) X \right], \\
B_3^W &= -i \frac{3}{4} V_{tb} V_{ts}^* r [a_8 Y + a_{10} - (a_7 - a_9) X]
\end{aligned} \tag{7}$$

where  $r = G_F f_K F_0^{B\pi}(m_K^2)(m_B^2 - m_\pi^2)$ ,  $X = (f_\pi/f_K)[F_0^{BK}(m_\pi^2)/F_0^{B\pi}(m_K^2)][(m_B^2 - m_K^2)/(m_B^2 - m_\pi^2)]$ ,  $Y = 2m_K^2/[(m_s + m_q)(m_b - m_q)]$  with  $q = u, d$  for  $\pi^{\pm,0}$  final states, respectively. In this analysis,  $f_\pi = 133$  MeV,  $f_K = 158$  MeV,  $F_0^{B\pi}(0) = 0.33$ ,  $F_0^{BK}(0) = 0.38$  [3, 15];  $|V_{cb}| = 0.0395$ ,  $|V_{cd}| = 0.224$  and  $|V_{ub}|/|V_{cb}| = 0.08$  [12]. The value of  $m_s$  is not known to a good accuracy, but a value around  $(100 - 120)$  MeV inferred from  $m_{K^*} - m_\rho$ ,  $m_{D_s^+} - m_{D^+}$  and  $m_{B_s^0} - m_{B^0}$  mass differences [16] seems not unreasonable and in this work, we use  $m_s = 120$  MeV.  $a_j$  are the effective Wilson coefficients after Fierz reordering in factorisation model and are given by [6]

$$\begin{aligned}
a_1 &= 0.07, \quad a_2 = 1.05, \\
a_4 &= -0.043 - 0.016i, \quad a_6 = -0.054 - 0.016i,
\end{aligned} \tag{8}$$

for the contributions from the tree-level and the strong penguin operators at  $N_c = 3$  and  $m_b = 5.0$  GeV. The strong penguin contribution  $P = a_4 + a_6 Y$ , as obtained from Eq.(8) is enhanced by the charm quark loop which increases the amplitude by 30% as pointed out in [9]. This enhancement brings the predicted branching ratios closer to the CLEO measured values, as shown in Fig.1. where the CP-averaged  $B \rightarrow K\pi$  branching ratios obtained for  $\gamma = 70^\circ$  [3], are plotted against the rescattering phase difference  $\delta = \delta_3 - \delta_1$ .

For a determination of  $\gamma$ , two quantities obtained from the sum of the two CP-averaged decay rates  $\Gamma_{B^-} = \Gamma(B^- \rightarrow K^- \pi^0) + \Gamma(B^- \rightarrow \bar{K}^0 \pi^-)$  and  $\Gamma_{\bar{B}^0} = \Gamma(\bar{B}^0 \rightarrow K^- \pi^+) + \Gamma(\bar{B}^0 \rightarrow \bar{K}^0 \pi^0)$  which are independent of  $\delta$  could be used [6]. As the CP-averaged  $B \rightarrow K\pi$  decay rates depend on  $\gamma$ , the computed partial rates  $\Gamma_{B^-}$  and  $\Gamma_{\bar{B}^0}$  would now lie between the upper and lower limit corresponding to  $\cos(\gamma) = 1$  and  $\cos(\gamma) = -1$ , respectively. As shown in Fig.2, where the corresponding CP-averaged branching ratios ( $\mathcal{B}_{B^-}$  and  $\mathcal{B}_{\bar{B}^0}$ ) for  $\Gamma_{B^-}$  and  $\Gamma_{\bar{B}^0}$  are plotted against  $\gamma$ , the factorisation model values with the BWS form factors [15] seem somewhat smaller than the CLEO central values by about 10 – 20%. Also,  $\mathcal{B}_{B^-} > \mathcal{B}_{\bar{B}^0}$  while the data give  $\mathcal{B}_{B^-} < \mathcal{B}_{\bar{B}^0}$  by a small amount which could be due to a large measured  $\bar{B}^0 \rightarrow \bar{K}^0 \pi^0$  branching ratio.

Note that smaller values for the form factors could easily accommodate the latest CLEO measured values, if a smaller value for  $m_s$ , e.g, in the range (80 – 100) MeV is used. What one learns from this analysis is that  $B \rightarrow K\pi$  decays are penguin-dominated and the strength of the penguin interactions as obtained by perturbative QCD, produce sufficient  $B \rightarrow K\pi$  decay rates and that factorisation seems to work with an accuracy better than a factor of 2, considering large uncertainties from the form factors and possible non-factorisation terms inherent in the factorisation model and the uncertainties in the penguin amplitude which is sensitive to the current  $s$  quark mass. Since the four  $B \rightarrow K\pi$  decay rates depend on only three amplitudes  $A_1$ ,  $B_1$  and  $B_3$ , it is possible to derive a relation between the decay rates independent of  $A_1$ . Thus, the quantity  $\Delta$  obtained from the decay rates,

$$\begin{aligned} \Delta &= \left\{ \Gamma(B^- \rightarrow \bar{K}^0 \pi^-) + \Gamma(\bar{B}^0 \rightarrow K^- \pi^+) \right. \\ &\quad \left. - 2 \left[ \Gamma(B^- \rightarrow K^- \pi^0) + \Gamma(\bar{B}^0 \rightarrow \bar{K}^0 \pi^0) \right] \right\} \tau_{B^0} \\ &= \left[ -\frac{4}{3} |B_3|^2 - \frac{8}{\sqrt{3}} \text{Re}(B_3^* B_1 e^{i\delta}) \right] (C \tau_{B^0}) \end{aligned} \quad (9)$$

is independent of the strong penguin term. It is given by the tree-level and electroweak penguin contributions. As can be seen from Fig.2, where its values for  $\delta = 0$  are plotted against  $\gamma$ .  $\Delta$  is of the order  $O(10^{-6})$  compared with  $\mathcal{B}_{B^-}$  and  $\mathcal{B}_{\bar{B}^0}$  which are in the range  $(1.6 - 3.0) \times 10^{-5}$ . Thus, to this level of accuracy, we can put  $\Delta \simeq 0$  and obtain the relation ( $r_b = \tau_{\bar{B}^0} / \tau_{B^-}$ ).

$$r_b \mathcal{B}_{\bar{K}^0 \pi^-} + \mathcal{B}_{K^- \pi^+} = 2 [\mathcal{B}_{\bar{K}^0 \pi^0} + r_b \mathcal{B}_{K^- \pi^0}] . \quad (10)$$

which can be used to test factorisation or to predict  $\mathcal{B}(\bar{B}^0 \rightarrow \bar{K}^0 \pi^0)$  in terms of the other measured branching ratios. Eq.(10) then predicts a central value  $\mathcal{B}(\bar{B}^0 \rightarrow \bar{K}^0 \pi^0) = 0.60 \times 10^{-5}$ .

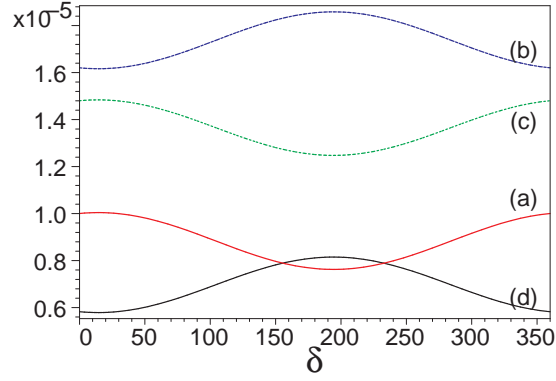


Figure 1:  $\mathcal{B}(B \rightarrow K\pi)$  vs.  $\delta$  for  $\gamma = 70^\circ$ . The curves (a), (b), (c), (d) are for the CP-averaged branching ratios  $B^- \rightarrow K^- \pi^0$ ,  $\bar{K}^0 \pi^-$  and  $\bar{B}^0 \rightarrow K^- \pi^+$ ,  $\bar{K}^0 \pi^0$ , respectively.

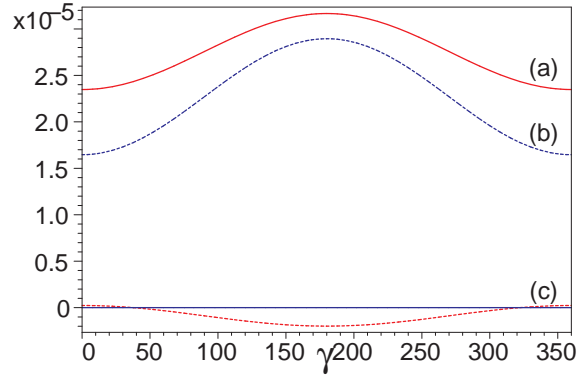


Figure 2:  $\mathcal{B}_{B^-}$  (a),  $\mathcal{B}_{\bar{B}^0}$  (b),  $\Delta$  (c) vs.  $\gamma$

Since  $\mathcal{B}_{\bar{K}^0\pi^0}$  is not known with good accuracy at the moment, it is useful to use another quantity, defined as

$$r_b\mathcal{B}_{\bar{K}^0\pi^-} + \mathcal{B}_{K^-\pi^+} = (C_1\tau_{\bar{B}^0}) \left[ \frac{1}{3}|B_3|^2 + (|A_1|^2 + |B_1|^2) - \frac{2}{\sqrt{3}}\text{Re}(B_3^*B_1e^{i\delta}) \right] \quad (11)$$

which contains a negligible  $\delta$ -dependent term of the order  $O(10^{-7})$ . The quantity  $R$  defined as

$$R = \frac{\mathcal{B}(B^- \rightarrow K^-\pi^0) + \mathcal{B}(B^- \rightarrow \bar{K}^0\pi^-)}{\mathcal{B}(B^- \rightarrow \bar{K}^0\pi^-) + \mathcal{B}(\bar{B}^0 \rightarrow K^-\pi^+)/r_b} . \quad (12)$$

is thus essentially independent of  $\delta$  and could also be used to obtain  $\gamma$ , as it does not suffer from large uncertainties in the form factors and in the CKM parameters. As can be seen in Fig.3, it is not possible to deduce a value for  $\gamma$  with the present data which give  $R = (0.80 \pm 0.25)$  as the prediction for  $R$  lies within the experimental errors. If we could reduce the experimental uncertainties to a level of less than 10%, we might be able to give a value for  $\gamma$ . Thus it is important to measure  $B \rightarrow K\pi$  branching ratios to a high precision. Also shown in Fig.3 are two other quantities more sensitive to  $\gamma$ , but involved  $\mathcal{B}(\bar{B}^0 \rightarrow \bar{K}^0\pi^0)$  and are given as [6]

$$R_1 = \frac{\Gamma_{B^-}}{\Gamma_{\bar{B}^0}} , \quad R_2 = \frac{\Gamma_{B^-}}{(\Gamma_{B^-} + \Gamma_{\bar{B}^0})} \quad (13)$$

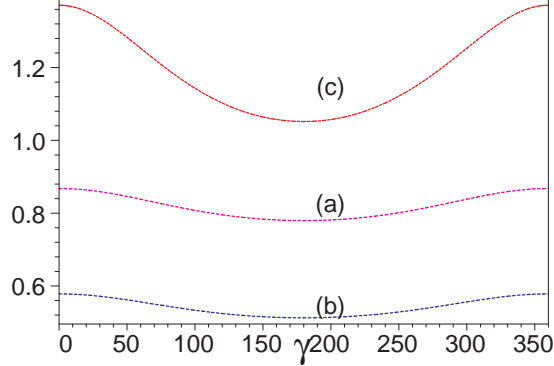


Figure 3: The curves (a), (b), (c) are for  $R$ ,  $R_2$ ,  $R_1$  respectively.

Thus a better way to obtain  $\gamma$  would be to use  $R_1$  when a precise value for  $\mathcal{B}(\bar{B}^0 \rightarrow \bar{K}^0\pi^0)$  will be available. The central value of 0.80 for  $R$  corresponds to  $\gamma = 110^\circ$ , close to the value of  $(113^{+25}_{-23})^\circ$  found by the CLEO Collaboration in an analysis of all known charmless two-body  $B$  decays with the factorisation model [17].

It seems that the CLEO data favor a large  $\gamma$  in the range  $90^\circ - 120^\circ$ . With a large  $\gamma$ , for example, with the central value of  $110^\circ$ , as shown in Fig.4, the predicted  $B \rightarrow K\pi$  branching ratios are larger than that for  $\gamma = 70^\circ$  and are closer to the data. The data also show that  $B^- \rightarrow \bar{K}^0\pi^-$  and  $\bar{B}^0 \rightarrow K^-\pi^+$  are the two largest modes with near-equal branching ratios in qualitative agreement with factorisation. However, for  $\gamma = 70^\circ$ , Fig.1 shows that these two largest branching ratios are quite apart, except for  $\delta < 50^\circ$  while for  $\gamma = 110^\circ$ , Fig.4 suggests that these two branching ratios are closer to each other only for  $\delta$  in the range  $40^\circ - 70^\circ$ . With  $\gamma < 110^\circ$  and some adjustment of form factors, the current  $s$  quark mass and CKM parameters, it might be possible to accommodate these two largest branching ratios with  $\delta < 50^\circ$ .

The CP-asymmetries, as shown in [6], for  $\gamma = 110^\circ$ , are in the range  $\pm(0.04)$  to  $\pm(0.3)$  for the preferred values of  $\delta$  in the range  $(40 - 70)^\circ$ , but could be smaller for  $\delta < 50^\circ$ . The CLEO measurements [18] however, do not show any large CP-asymmetry in  $B \rightarrow K\pi$  decays, but the errors are still too large to draw any conclusion at the moment.

In conclusion, factorisation with enhancement of the strong penguin contribution seems to describe qualitatively the  $B \rightarrow K\pi$  decays, Further measurements will allow a more precise test of factorisation and a determination of the weak angle  $\gamma$  from the FSI phase-independent relations shown above.

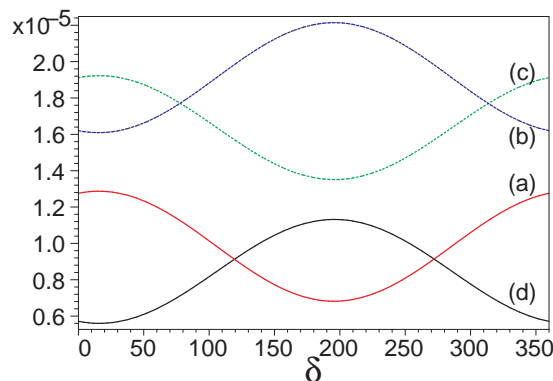


Figure 4:  $\mathcal{B}(B \rightarrow K\pi)$  vs.  $\delta$  for  $\gamma = 110^\circ$ . The curves (a), (b), (c), (d) are for the CP-averaged branching ratios  $B^- \rightarrow K^-\pi^0$ ,  $\bar{K}^0\pi^-$  and  $\bar{B}^0 \rightarrow K^-\pi^+$ ,  $\bar{K}^0\pi^0$ , respectively.

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